Appendix E

Fluid Jet Cutting of Davis-Besse RPV Head Materials

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E.1 Introduction

The formation of the wastage cavity in the reactor pressure vessel (RPV) head of the Davis Besse nuclear reactor was most likely due to a combination of degradation mechanisms. While the Root Cause Report for this incident identified boric acid corrosion as the primary mechanism for head wastage, subsequent observations and fluid flow modeling efforts suggest alternative mechanisms that may have significantly influenced wastage cavity formation. In addition to flow-assisted corrosion (FAC), mechanical mechanisms for metal removal from the RPV head may also have played an important role. These mechanical mechanisms include water jet cutting and abrasive water jet cutting. If these mechanical material removal mechanisms were the dominant degradation mechanism for material removal, the wastage cavity could have formed in a relatively short (days to weeks) period of time, in contrast to the corrosion time (4 years) estimated in the Root Cause Report.[1]

E.2 Pure Water Jet Cutting

The primary mechanism for material removal by water jet cutting is the conversion of the kinetic energy of the jet into the stagnation pressure at the point of impact on the target. The maximum pressure "P_J", which can be produced (above the ambient static pressure) by such a jet, is related to the jet velocity "V_0" by the following relationship,

$$P_J = \tfrac{1}{2} \rho V_0^2 \qquad \text{(Eqn. 1)}$$

where ρ is the density of the fluid in the jet.[2] At a temperature of 600°F and a pressure of 2000 psig, the specific volume of water is 0.02330 ft^3/lb,[3] which yields a density of 0.0248 lb/in^3.

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An evaluation of critical and optimum parameters for the material removal by water jet cutting was completed by Hashish.[4] The minimum pressure required to remove material by the impingement of a water jet was a pressure equal to the yield stress (σ_y) of the material. A detailed evaluation of the total specific energy required for water jet cutting yielded an "optimum" pressure "P_o" for material removal in a ductile material as,

$$P_o = 2.5\ \sigma_y \qquad \text{(Eqn. 2)}$$

where σ_y is the yield stress for the ductile material.[5] A typical yield stress for carbon steel at room temperature (75°F) is 50,000 lb/in^2. However, the yield stress for carbon steel is lower at reactor operating temperatures. As noted by Glasstone and Sesonske,[6] the allowable stress for carbon steel (A302-B) under reactor conditions at 700°F is 27,000 lb/in^2. Hence, a reasonable estimate for the allowable stress for carbon steel at 600°F is approximately 30,000 lb/in^2. Therefore, the minimum and optimum pressures for water jet removal of carbon steel at reactor temperatures are approximately 30,000 lb/in^2 and 75,000 lb/in^2, respectively.

The water jet velocities required to begin material removal and the optimum velocity for material removal can be estimated by rearranging Equation 1 and solving for V_0.

$$V_0 = (2\sigma/\rho)^{½} \qquad \text{(Eqn. 3)}$$

where σ is the yield stress and 2.5 times the yield stress for the minimum and optimum material removal conditions. The results of these calculations suggest that a minimum fluid velocity of 2,386 feet per second is required to begin material removal. The fluid velocity for optimum material removal using only a water jet is 3,773 feet per second. These velocities are 2 to 3 times the sonic velocity in air at 600°F

E.3 Abrasive Water Jet Cutting

The material removal rate is greatly increased by the introduction of very fine abrasive materials into a water jet fluid flow stream. This technology, called the abrasive water jet technique, has been developed for industrial applications over the past 25 years. In abrasive water jet technology, abrasives are incorporated into a high-velocity water jet and the momentum of the water is transferred to the abrasive particle, rapidly increasing the velocity of the particle. Typical abrasive water jet fluid velocities are 300-600 m/s (984–1,968 ft/s) with abrasive mass flow rates of approximately 10 grams per second.[7] Current industrial applications of abrasive water jet cutting employ fluid flow rates of 0.5 gallons per minute (gpm) with an orifice diameter of 0.010 inch.[8]

Early investigations of the efficacy of abrasive water jet technology were completed by Hashish. Studies of the experimental conditions for the optimum abrasive water jet cutting of steel, cast iron, aluminum, and Inconel were presented by Hashish. The effect of abrasive type (garnet, silica sand and glass beads), abrasive flow rate, and stand-off distance were evaluated using a range of flow conditions and abrasives. Typical material removal rates for mild steel over a range of stand-off distances from the nozzle exit to the cutting surface at various flow rates are shown in Table E.1.[9]

Table E.1 Effect of Standoff Distance and Abrasive Flow Rate on the Material Removal Rate in Abrasive Water Jet Cutting of Mild Steel[9]

Abrasive Flow Rate	4.3 g/s	7.3 g/s	10.7 g/s
Standoff	Removal Rate		
Distance (mm)	(mm^3/sec)	(mm^3/sec)	(mm^3/sec)
2.5	22	34	95
5	34	42	72
10	32	51	64
20	30	42	55
50	18	22	50
75	10	18	43

Additional comparisons of material removal rates for a range of materials and cutting parameters were also presented by Hashish[10] and are shown in Table E.2.

Table E.2 Material Removal Rate for Abrasive Water Jet Cutting of Various Materials[10]

Material	Removal rate mm^3/s)
Aluminum	50-300
Steel	40-200
Cast Iron	50-250
Titanium	50-250
Inconel	40-200

E.4 Estimated Material Removal Rate

Following the initiation of boric acid precipitation and RPV head corrosion, ample amounts of abrasive material were available for incorporation into the fluid stream ejected from the CRDM nozzle crack. With hundreds of pounds of crystalline boric acid and the corrosion of about 195 in^3 of carbon steel (approximately 55 lb of steel yielding approximately 75 lb of Fe_3O_4), there were significant quantities of abrasive materials that could be entrained in the high-velocity fluid jet striking the interior surfaces of the wastage cavity.

The Root Cause Report estimated that the leakage attributed to CRDM nozzle leaks during late 2001 was 0.1 to 0.2 gpm[11.] Our calculations of CRDM crack leak rates, presented in Section 9.4, determined that the CRDM Nozzle 3 leak rate was on the order of 0.17 gpm at this time. An estimate of the total material wastage that could have occurred due to this leak rate during this time period by abrasive jet cutting can be made by using data in Table E-1. Scaling the material removal rate for the 75 mm (3 inch) standoff distance at the lowest abrasive material flow rate (4.3 g/s) by the ratio of the flow rates (34% - 0.17 gpm/0.5gpm) yields a material removal rate of approximately 3.4 mm^3/s. At this material removal rate, the time required to excavate a wastage cavity of 195 in^3 (3,195,500 mm^3) would have been 939,853 seconds (261 hours = 10.8 days).

Therefore, under optimum abrasive water jet cutting conditions, the entire wastage cavity could have formed in a period of a couple of weeks.

E.5 Evidence Supporting Mechanical Removal of Material from the Wastage Cavity

No specific evaluations of the metallic particle content of the boric acid or corrosion deposits removed from the RPV head and wastage cavity near Nozzle 3 during 13 RFO were completed. However, two chemical analyses of the deposits removed from the Davis-Besse reactor vessel head were completed by Framatome ANP in June 2002 and July 2002, respectively.[12-13] The initial analyses on a number of specimens collected from the RPV were completed by Fender.[11] This study noted that one of the specimens, "The dark colored chunk was quite hard and not easily crushed; a metallic strip coated with an adherent deposit was revealed after crushing." The chemical analysis was completed after the removal of the metal strip.

Subsequent chemical analyses were completed by Cyrus,[13] who noted, "Metallic fragments that could be readily isolated from the bulk deposit samples were removed. The remaining material in each sample was homogenized by grinding in an agate mortar and pestle. Portions of the homogenized samples were then segregated for analysis. Because smaller metallic particles remained in the samples, any metallic iron detected in the samples by x-ray diffraction was ignored."

Since the chemical analyses of the materials removed from these metallic samples contained little chromium, it is evident that the source of this metal was not the degradation of the mirror insulation or the machining of CRDM nozzle flange surfaces during prior outages. Fender noted that, "The most probable source of the iron is the carbon steel of the reactor vessel head".[14] These observations support the case that mechanical removal of reactor pressure head material occurred during the formation of the wastage cavity. The mechanical removal of metallic fragments was likely a result of water jet cutting or abrasive water jet cutting of the RPV head during periods of high nozzle leakage late in Cycle 13.

E.6 Observation

A major portion of the wastage cavity formation occurred during a relatively short period of time of the order of days to weeks, late in Cycle 13 and was due to abrasive water jet mechanisms that acted in conjunction with flow assisted boric acid corrosion.

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